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PROVING GROUNDS

May 1954

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OPERATION CASTLE

Project 7.2

DETECTION OF AIRBORNE LOW-FREQUENCY SOUND FROM NUCLEAR EXPLOSIONS

REPORT TO THE TEST DIRECTOR

U. S. MILITARY AGENCIES MAY OBTAIN COPIES OF THIS REPORT DIRECTLY FROM DDC. OTHER ... REQUEST THROUGH Sponsoring Agency to:

by

G. B. Olmsted

Director Defense Atomic Support Agency Washington, D. C. 20301

May 1955

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Headquarters United States Air Force
Office for Atomic Energy, DCS/O
AFOAT-1

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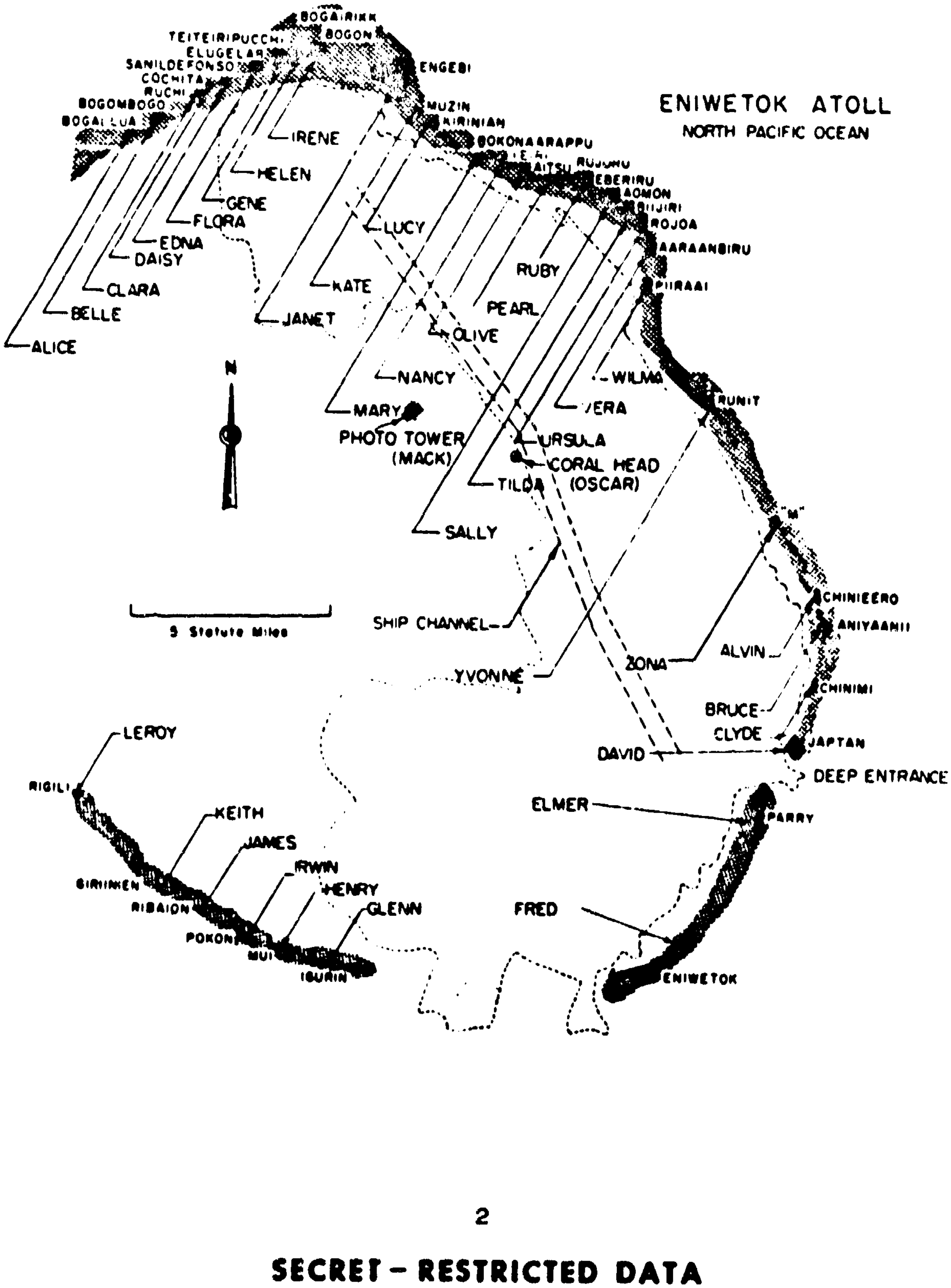

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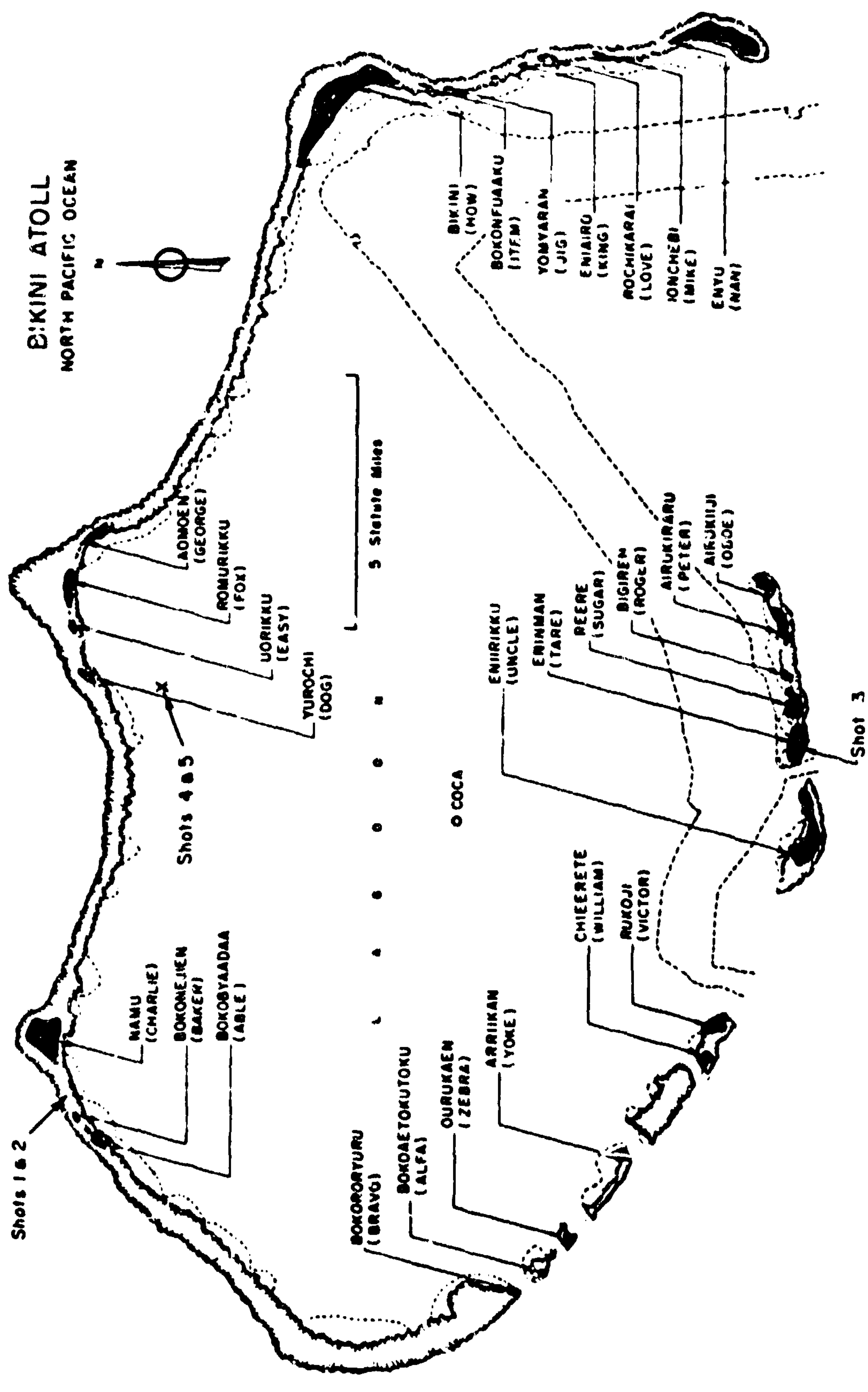
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IONCHEBI (MIKE)
ENYU (NAN)
AOMOEN (GEORGE)
ROMURIKKU (FOX)
UORIKKU (EASY)
YUROCHI (DOG)
Shots 4 & 5
ENIIRIKKU (UNCLE)
ERINNAN (TARE)
REERE (SUGAR)
BIGIREN (ROGER)
AIRUKIRARU (PETER)
AIRUKIIJI (OBOE)
Shot 3
O COCA
CHIEERETE (WILLIAM)
RUKOJI (VICTOR)
NAMU (CHARLIE)
BOKONEJIEN (BAKER)
BOKOBYAADAA (ABLE)
Shots 1 & 2
BOKORORYURU (BRAVO)
BOKOAETOKUTOKU (ALFA)
OURUKAEN (ZEBRA)
ARRIIKAN (YOKE)

GENERAL SHOT INFORMATION

	Shot 1	Shot 2	Shot 3	Shot 4	Shot 5	Shot 6
DATE	1 March	27 March	7 April	26 April	5 May	14 May
CODE NAME (Unclassified)	Bravo	Romeo	Koon	Union	Yankee	Nectar
TIME*	06:40	06:25	06:15	06:05	06:05	06:15
LOCATION	Bikini, West of Charlie (Namu) on Reef	Bikini, Shot 1 Crater	Bikini, Tare (Eninman)	Bikini, on Barge at Intersection of Arcs with Radii of 6900' from Dog (Yurochi) and 3 Statute Miles from Fox (Aomoen)		Eniwetok, IVY Mike Crater, Flora (Elugelab)
TYPE	Land	Barge	Land	Barge	Barge	Barge
HOLMES & NARVER COORDINATES	N 170,617.17 E 76,163.98	N 170,635.05 E 75,950.46	N 100,154.50 E 109,799.00	N 161,698.83 E 116,800.27	N 161,424.43 E 116,688.15	N 147,750.00 E 67,790.00

* APPROXIMATE

ABSTRACT

Measurements of the airborne low-frequency sound from the Operation CASTLE nuclear explosions were made at 15 remote locations, covering a variety of distances and directions from the Pacific Proving Grounds, with the objective of studying the relation between signal characteristics and the energy released over the range of yields from 1 to 15 megatons equivalent. Both standard and very low-frequency sound recording equipment responsive to small atmospheric pressure variations in the frequency range from 1.0 to 0.002 cycles/second were employed. Signals were detected at ranges exceeding 45,000 km for explosions larger than 5 MT, 30,000 km for the 1.7 MT shot, and 10,000 km for the 0.13 MT shot. All megaton shots produced the initial dispersive wave train of very low-frequency previously noted for IVY MIKE.

PREFACE

Conclusions given in this report are those of AFOAT-1, Headquarters U. S. Air Force, and do not necessarily reflect the opinions of agencies participating in the project.

FOREWORD

This report is one of the reports presenting the results of the 34 projects participating in the Military Effects Tests Program of Operation CASTLE, which included six test detonations. For readers interested in other pertinent test information, reference is made to WT-934, Summary Report of the Commander, Task Unit 13, Programs 1 - 9, Military Effects Program. This summary report includes the following information of possible general interest.

a. An over-all description of each detonation, including yield, height of burst, ground zero location, time of detonation, ambient atmospheric conditions at detonation, etc., for the six shots.

b. Discussion of all project results.

c. A summary of each project, including objectives and results.

d. A complete listing of all reports covering the Military Effects Tests Program.

ACKNOWLEDGMENTS

The data presented in this report were the result of measurements and analyses by the National Bureau of Standards, the Navy Electronics Laboratory, and the Signal Corps Engineering Laboratories. Credit for the success of Project 7.2 is due each of the participants listed below.

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CHAPTER 1

INTRODUCTION

1.1 OBJECTIVES

The primary objective of Project 7.2, Operation CASTLE, was to record and analyze the airborne acoustic waves generated by the thermonuclear explosions in order to provide calibration data for use in the interpretation of acoustic signals from foreign nuclear explosions. Additional important objectives included a delineation of the capabilities and limitations of standard detection equipment and a study of the relation of various signal characteristics to the total energy released in the explosion. A secondary objective was the collection of data on the propagation of dispersive waves from a very large atmospheric pressure pulse with the hope of eventual interpretation in terms of the temperature and wind structure in the upper atmosphere.

1.2 BACKGROUND

Remote acoustic measurements have been made during all previous United States nuclear tests except TRINITY (July 1945). The purpose of participation in CROSSROADS (July 1946), SANDSTONE (April and May 1948), and GREENHOUSE (April and May 1951) was to establish the feasibility of acoustic detection of nuclear explosions of moderate yield at distances in excess of 4000 km, since at least that range was necessary if a reasonably efficient acoustic monitoring system for foreign explosions was to be established. Results from CROSSROADS1,2/* and from SANDSTONE3/ were discouraging since the maximum distance for positive detection was only 1900 km. The use of improved detection equipment and techniques, however, resulted in detection of each nuclear explosion of GREENHOUSE4-7/ at a range of at least 4500 km.

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* Numbers refer to the reference list at the end of the report.

Continued participation in subsequent nuclear tests was required in order to delineate the capabilities and limitations of acoustic detection techniques for explosions of a wide range of yields detonated in the air, on the ground, and shallow underground during different seasons of the year. Results from Operation BUSTER-JANGLE (October and November 1951),8/ Operation TUMBLER-SNAPPER (April to June 1952),9/ and Operation UPSHOT-KNOTHOLE (March to June 1953)10/ indicated a limited but usable detection range for shots of small yield even though detonated shallow underground. Seasonal shifts in propagation, originally noted during tests using small TNT charges,11/ were confirmed. Amplitudes were found to depend markedly on propagation conditions and correlation between signal period and yield proved quite variable. Results from Operation IVY (November 1952)12/ showed that acoustic signals from large kiloton and megaton explosions were distinguished from signals from smaller explosions by longer range of detection, generally increased amplitudes, longer periods, and generally longer durations. In addition, the megaton explosion produced a characteristic dispersive train of acoustic waves not previously observed for man-made explosions. These waves were similar to the waves produced by the Great Siberian Meteor (June 1908).13/

Operation CASTLE provided an excellent opportunity to study the acoustic waves from explosions ranging from yields of the order of the larger GREENHOUSE shots to yields larger than the IVY shots. In particular, it offered the possibility of setting a lower limit of explosion size required to generate dispersive waves in the atmosphere.

No adequate theory of the propagation of a pressure pulse in the atmosphere is available. Pekeris13/ and Scorer14/ have developed the theory for simplified atmospheric models but experimental results give only qualitative resemblance to the theoretical results.

CHAPTER 2

EXPERIMENT DESIGN

2.1 PARTICIPATING AGENCIES

Project 7.2 was conducted jointly by the Signal Corps Engineering Laboratories (SCEL), the National Bureau of Standards (NBS), and the Navy Electronics Laboratory (NEL), under the sponsorship of AFOAT-1, Headquarters U. S. Air Force. The Office of the Chief Signal Officer coordinated the Army effort and the Office of Naval Research coordinated the Navy effort.

The Geophysics Research Directorate of the Air Force Cambridge Research Center (AFCRC) conducted additional measurements during CASTLE under a program separate from the weapons effects program. Although detailed results will be presented in a special AFCRC report, brief reference will be made here to significant high-lights of this work.

2.2 STATION LIST

Table 2.1 lists the stations making up the network for CASTLE and Fig. 2.1 shows the geographical distribution of those stations. Stations operated by AFCRC under the separate program mentioned above are also included in the table for informational purposes. The table gives the geographic coordinates of each station, the average great circle distance from the station to the Bikini and Eniwetok test sites, and the average azimuth from the station to the test sites measured clockwise from true north. Actual distances and azimuths to the individual shot locations differ slightly from values listed in the table.

2.3 SHOT DATA

Information regarding the date, unclassified code name, location, time, condition, and yield of each CASTLE shot is listed in Table 2.2. Figures showing the relative positions of shot locations in Eniwetok and Bikini Atolls may be found on pages 2 and 3.

2.4 STATION LAYOUT

Each station operated by the Signal Corps consisted of four microphone outposts, one at each corner of a quadrilateral, approximately square, 4 to 10 miles on a side. Each outpost was connected by wire lines to a recording central.

The NEL operated arrays of two to five microphone outposts spaced from 3 to 15 miles apart at San Diego, Twenty-Nine Palms, and Gila Bend. In most instances the microphone outposts were connected to a recording central at each station by wire lines or radio link. In a few cases, microphone output was recorded in the immediate vicinity of the microphone. A single microphone was operated at Los Angeles.

The NBS station consisted of six microphone outposts located at the corners of two roughly equilateral triangles, one having 2½-mile sides and the other 14-mile sides. The small triangle was roughly centered inside the larger triangle. Each outpost was connected by wire lines to a recording central.

AFCRC stations were similar to those of the Signal Corps except that individual recordings were made in the immediate vicinity of each microphone outpost.

2.5 INSTRUMENTATION

2.5.1 General

The equipment operated for CASTLE was practically identical with that used during IVY[12] except that attempts were made to improve the stability and reliability. Two main types of equipment were used during CASTLE: (1) standard detection equipment most responsive to atmospheric pressure changes having periods ranging roughly from 1 to 60 sec, and (2) very low-frequency equipment responsive to change in pressure or to rate-of-change of pressure for signal periods ranging approximately from 5 to 300 sec.

2.5.2 SCEL Instrumentation

Standard detection equipment was employed at all SCEL stations. Data Recording System M-2 [15] was operated at Kyoto and Hachinohe and NBS Infrasonic Microphone System[16] was operated at Oahu, Thule, Hanau, Belmar, and Fairbanks throughout the tests. The Zweibrucken and Clark Field Stations became operational starting with Shot 2 and employed the latter equipment. An improved version of the M-2 system was operated at Ft. Lewis. Both types of equipment utilized condenser microphones as the pressure-sensitive transducers, wire lines for transmission of the electrical signal from the outposts to the recording central, and Esterline-Angus C-1 or 0-3 ma graphic recorders. The M-2 employed a capacitance bridge and a phase-sensitive discriminator to produce a voltage at the same frequencies as the pressure fluctuations. This slowly varying voltage was transmitted over the wire lines and was amplified at the recording central.

The NBS system used the microphone as the frequency-controlling element in a Wien-bridge oscillator to produce a frequency-modulated signal for transmission over the wire lines to the recording central where the signal was demodulated by a pulse-count type discriminator and then amplified. The M-2 equipment responded mainly to pressure changes in the range of periods from 1 to 50 sec and the NBS from 1 to 35 sec. The maximum sensitivity for the M-2 was of the order of 15-mm deflection for a pressure change of 1 dyne/cm^2, that for the improved M-2 was about 45-mm/dyne/cm^2, and that for the NBS was approximately 30-mm/dyne/cm^2 during CASTLE. The recording speed for these instruments was 3 in./min.

Very low-frequency equipment, covering periods from 5 to 300 sec, was operated at Belmar for the entire test series; at Oahu, Fairbanks, and Ft. Lewis for all shots except Shot 1; and at Kyoto for all shots except 1 and 2. This equipment consisted of a special condenser microphone designed for low-frequency response through use of a very large reference volume, a high-resistance acoustic leak, and elaborate thermal insulation. The electronic and control circuits were similar to that employed in the improved M-2 equipment and the maximum sensitivity was approximately the same as that for the improved M-2 equipment. The Esterline-Angus graphic recorders were operated at a tape speed of 1.5 in./min.

Each standard microphone was equipped with a linear, multiple-inlet pipe array, 1000 ft in length, designed to reduce the noise background from atmospheric turbulence. No effective array was available for use at very low-frequencies.

2.5.3 NEL Instrumentation

Two types of very low-frequency equipment were operated by the NEL. The first type, employed at San Diego and Gila Bend, consisted of a Rieber vibrotron microphone[17] modified for response mainly to periods from 8 to 265 sec by use of appropriate acoustic leaks, low-frequency amplifiers, and thermal insulation. Output was recorded on a six-channel Brush graphic recorder, using a paper speed of 0.2 in./min. at San Diego and 0.5 in./min. at Gila Bend.

The other type of equipment, operated at all NEL stations, consisted of a Signal Corps T-21-B condenser microphone modified to respond mainly to periods from 6 to 300 sec by use of appropriate acoustic leaks, special low-frequency amplifiers, and elaborate thermal insulation. The output of each microphone was recorded on an Esterline-Angus graphic recorder at 0.75 in./min. In addition, the output of one microphone each at San Diego, Twenty-Nine Palms, and Gila Bend was recorded on magnetic tape for the purpose of studying the frequency spectrum of recorded signals. At maximum sensitivity, the modified Rieber equipment gave a deflection of approximately 0.2-mm for a pressure change of 1 dyne/cm^2 and the modified T-21-B equipment gave approximately 0.7-mm/dyne/cm^2.

No effective noise-reducing arrays were available for use at very low frequencies.

2.5.4 NBS Instrumentation

All six outposts at the NBS station in Washington, D. C., were equipped with standard NBS equipment[16] similar to that described in section 2.5.2. The microphone was modified by increasing the reference volume and increasing the resistance of the acoustic leak so that the sensitivity was increased but the frequency response remained the same. At maximum sensitivity, the equipment gave a deflection of approximately 50 mm for a pressure change of 1 dyne/cm^2. A standard linear pressure-averaging pipe array of Signal Corps design, approximately 1000 ft in length, was connected to each microphone. Normal tape speed of the Esterline-Angus graphic recorders was 3 in./min.

The three microphones making up the large triangle (see section 2.4) and one of the microphones from the small triangle were also connected to special multivibrator-type discriminators and low-pass filter-amplifiers to produce a response to rate-of-change of pressure down to very low frequencies. This equipment was operated at a sensitivity which gave approximately 50-mm deflection on an Esterline-Angus graphic recorder for a rate-of-change of pressure of 1 dyne/cm^2/sec. This means that a sinusoidal pressure change of 1 dyne/cm^2 at a period of 300 sec would produce a deflection of 1 mm. A tape speed of 0.75 in./min. was employed.

Five of the standard channels and five of the very low frequency channels were recorded directly on magnetic tape for use in correlation and spectrum studies.

2.5.5 AFCRC Instrumentation

AFCRC operated the modified T-21-B equipment developed by NEL. (See section 2.5.3) Tape speeds and sensitivities were approximately the same as that used by NEL.

2.5.6 Timing

Absolute timing was obtained by reference to radio signals from WWV and WWVH. Interval timing was accomplished through use of uniform rate devices: chronometers, flasher motors, and direct marking from WWV interval signals.

CHAPTER 3

RESULTS AND DISCUSSION

3.1 GENERAL

The results of analysis of graphic records from both standard and very low-frequency instrumentation are listed in Tables 3.1 to 3.11, inclusive. Data include the time of arrival of the first detectable signal or, in the case of some very low-frequency recordings, the time of arrival of the first positive peak; the time of arrival of the maximum amplitude; the average azimuth of the incoming acoustic wave measured in degrees clockwise from true north; the range of horizontal phase velocity or the average velocity observed throughout the wave train; the maximum signal amplitude*; the total duration of the wave train; the observed signal periods; and the average noise amplitude just before and just after the arrival of the acoustic signal. The "first wave" or "direct wave" refers to the signal arriving by the most direct great circle path from the explosion site, the "second wave" or "antipodes wave" refers to the arrival via the antipodes of the explosion site, etc.

Results of analysis of magnetic-tape recordings are presented in pertinent sections throughout this chapter.

3.2 DETECTION RANGE

Each CASTLE shot of equivalent yield in the megaton range was detected on standard equipment at very great distances from the explosion. Every operative station detected the direct wave from these five shots (1, 2, 4, 5, and 6). Four of the nine operational stations detected the wave via the antipodes for Shot 1, 7 of 11 for Shot 2, 4 of 11 for Shot 4, 8 of 11 for Shot 5, and 2 of 11 for Shot 6. In addition, 4 stations detected the second passage of the direct wave

* All amplitudes are uncorrected for equipment response except those reported by NBS.

for Shot 1, 3 for Shot 2, 2 for Shot 4, 2 for Shot 5, and none for Shot 6. The Clark Field station detected possible second antipodes arrivals from Shots 4 and 5. Maximum detection ranges were 51,470 km for Shot 1; 46,940 km for Shot 2; 75,200 km for Shots 4 and 5, and 32,080 km for Shot 6. It should be noted that some of the recordings from extreme ranges are of somewhat doubtful validity.

Only four stations detected the direct wave from Shot 3 and the maximum detection range was 11,470 km. None of the stations to the west of the explosion detected the acoustic waves from Shot 3 although three stations were arrayed between 3960 and 4860 km from the explosion.

As has been noted during previous tests, detection ranges were generally less for very low-frequency (VLF) equipment than for the standard equipment due to the greater noise recorded on the lower frequency equipment. However, every operational VLF station detected the direct wave from the four largest shots (1, 2, 4 and 5), most detected Shot 6, but only Oahu detected Shot 3. Maximum detection ranges were 31,890 km for Shot 1; 25,140 km for Shots 2, 4, and 5; 4040 km for Shot 3; and 18,100 km for Shot 6.

3.3 SIGNAL CHARACTERISTICS

3.3.1 General

Character of the direct wave from the four largest CASTLE shots is illustrated in Fig. 3.1 which shows greatly reduced-scale tracings of recordings at San Diego. Somewhat larger-scale tracings from IVY Mike and CASTLE Shot 1 are included for the purpose of comparison. All very low-frequency recordings from megaton shots showed the dispersive train of waves noted for IVY Mike. However, each shot produced significant differences in the variations in period and amplitude with time. Significant changes in the dispersive train with distance and direction were also noted, but it will be necessary to await the AFCRC report for greater detail. No dispersive train was observed on recordings from Shot 3.

Most recordings on standard equipment also showed definite evidence of at least a portion of the dispersive train for the four largest shots although the amplitudes were greatly reduced by lack of low-frequency response.

Antipodes and second direct arrivals on VLF equipment also showed marked evidence of the dispersive train in cases of high signal-to-noise ratio.

3.3.2 Horizontal Phase Velocities

An accurate measurement of the horizontal phase velocities for the long signal periods (and correspondingly long wave-lengths) observed in the initial part of the dispersive train was believed possible only by using the very large triangles operated by NEL in the California-Arizona region. These triangles consisted of Los Angeles - San Diego - Twenty-Nine Palms and San Diego - Twenty-Nine

Palms - Gila Bend. The first of these triangles was about 200 km on a side while the latter was composed of 200-, 350-, and 400-km legs. Phase velocities reported by NEL ranged from 315 to 325 meters per second for Shot 1, 322 to 327 for Shot 2, 317 to 325 for Shot 4, and 315 to 325 for Shot 5. These values were slightly lower than the normal velocity of sound at ground level (about 335) and are nearly equal to the travel speeds for first arrivals at these locations. Theoretical studies predicted phase velocities equal to the speed of sound at ground level — i.e., vertical wave-fronts.

Horizontal phase velocities obtained from standard equipment at stations where the microphone spacing was, in general, small compared to the wave-length of the acoustic signal showed a considerable range of values. However, practically every first-wave signal gave phase velocities covering some portion of the range from 318 to 360 meters per second. Second, third, and fourth-wave arrivals gave greater spreads in phase velocities than did first-wave arrivals. This may be attributable, at least partially, to the generally lower signal-to-noise ratios for the later wave arrivals.

3.3.3 Signal Amplitudes

Data on signal amplitudes are subject, in many cases, to considerable error due to the fact that the signal periods lay outside the pass-band of the equipment. Only the data from the NBS Washington station have been corrected for response. In general, amplitudes reported for very low-frequency equipment should be of greater accuracy for the longer periods than amplitudes reported for standard equipment. Difficulties in calibrating the very low-frequency instrumentation and in maintaining an accurate calibration under field conditions throw considerable doubt on the accuracy of these measurements.

As expected, the high-sensitivity of the standard equipment resulted in many off-scale signals. As noted in previous tests, amplitudes generally decreased with distance from the explosion site. However, very large variations in amplitude prevent more than a qualitative statement of this relationship.

A detailed study of the amplitudes recorded by very low-frequency equipment is being undertaken by AFCRC. Results will be reported separately by that organization at a later date.

3.3.4 Signal Duration

Detectable signal for direct wave arrivals on standard equipment persisted for a minimum of 8 min and a maximum of 369 min, the average being 74. Antipodes and later arrivals persisted for a minimum of 3, a maximum of 530, and an average of 140 min.

For very low-frequency equipment, the direct wave signals persisted for a minimum of 9, a maximum of 240, and an average of 79 min. Antipodes and later arrivals gave a minimum of 83, a maximum of 339, and an average of 192 min.

The duration of the signal depended greatly upon the noise level at the recording station.

3.3.5 Signal Periods

The frequency content of the signal was studied both by visual analysis of graphic records and by machine analysis of magnetic tape recordings. VLF recordings were used mainly to reveal the long periods occurring in the dispersive train and the standard recordings were used in the study of the shorter periods in the later arrivals.

In general, signals from the megaton shots started with an increase of pressure followed by a larger negative pulse. The first measurable periods generally ranged from 200 to 450 sec and were followed by decreasing periods at later times, at least for the first 30 min. Many of the recordings showed later arrivals of non-dispersive character.

Short period arrivals characteristic of waves trapped by temperature and wind gradients in the first few thousand feet of the atmosphere were observed at the beginning of some recordings at stations within 5000 km of the explosion. Such waves had occasionally been observed at stations within 1000 km of previous U. S. explosions, but never at such long ranges. Periods in these arrivals were of the order of 3 to 5 sec and persisted for as long as 5 min.

3.4 TRAVEL SPEEDS

The speed of travel of the acoustic wave, computed by dividing the great circle distance from source to station by the total elapsed time required for that travel, is presented in Tables 3.12 and 3.13.

The average speed of travel of the first recognizable signal from the direct wave on standard equipment was 310 meters per second for Shot 1, 308 for Shots 4 and 5, 307 for Shot 2, and 288 for Shot 3. Average speeds for stations to the east and northeast of the explosion site were somewhat higher than average speeds to the west and northwest of the site for Shots 1 and 2 but the reverse was true for Shots 4, 5, and 6. This is apparent from the following eastward versus westward speeds: 316 vs. 307 for Shot 1, 309 vs. 305 for Shot 2, 288 vs. 289 for Shot 3, 306 vs. 315 for Shot 4, 309 vs. 311 for Shot 5, and 294 vs. 315 for Shot 6.

Comparing speeds to Oahu toward the east and to Clark Field toward the west since these stations were at approximately equal distances from the site, note that Oahu gave a speed of 318 for Shot 2 compared to 306 for Clark Field, 312 against 289 for Shot 3, 303 compared to 319 for Shot 4, 318 to 314 for Shot 5, and 292 compared to 320 for Shot 6. Clark Field was not in operation for Shot 1, but Oahu reported a high speed of 335 m/sec. Except for Shot 5 data, the general trend was toward decreasing speeds eastward and increasing speeds westward as the CASTLE series progressed from 28 February to 13 May.

The average travel speed for first arrivals from the direct wave on VLF equipment ranged somewhat higher than speeds obtained from standard recordings. Over-all average speeds for all VLF recordings from direct waves were 319 for Shot 1, 321 for Shot 2, 310 for Shot 3, 317 for Shot 4, 315 for Shot 5, and 302 for Shot 6. These higher speeds were due to the earlier arrival of the long-period dispersive train recorded on VLF equipment. Frequently, noise obscured some of

these long periods on standard equipment. Directional trends in VLF speeds were not immediately apparent. However, more detailed studies of these effects will be undertaken by AFCRC.

3.5 AZIMUTH ERRORS

The difference between the true azimuth from the station to the explosion site and the observed azimuth of the incoming acoustic wave is given in Table 3.14 for standard recordings. Normally, the azimuth measurements were restricted to signal periods less than about 100 sec in order to obtain accuracies approximately equivalent to that obtained for smaller explosions. For distances less than 12,000 km from the explosion site, the maximum observed azimuth error was 11.5° and the average error was 3.2°. At longer distances, much larger errors were reported. No consistent pattern of azimuth errors was observed which could be related to the direction the acoustic wave traveled from the source. In many instances, stations within a few hundred miles of each other reported large differences in azimuth errors. For example, errors at Kyoto and Hachinohe differed by 4.6, 2.6, 3.5, 11.5, and 0.2 degrees for shots 1, 2, 4, 5, and 6 respectively.

Azimuth errors for the dispersive wave could not be accurately determined at most stations because the separation between microphones was small compared to the wave-lengths of the acoustic wave. However, reasonable accuracies were possible for the large NEL station arrays in the California-Arizona region. The average errors observed by NEL were 10° for Shot 1, 4° for Shot 2, 6° for Shot 4, and 2° for Shot 5.

3.6 YIELD

Attempts have been made to relate various characteristics of acoustic signals at great distances to the total energy released by the nuclear explosion. Critical dependence of signal amplitude on the variable temperature and wind structure in the upper atmosphere coupled with difficulties in the accurate measurement of amplitude led to a search for more reliable indicators of yield. Dr. A. B. Focke* suggested a possible connection between signal frequency and yield, postulating a cube-law relationship based upon general scaling considerations. Maynard Cowan[17] of the Sandia Corporation verified this cube-law relationship between the duration of the first negative pulse and yield for acoustic records at ranges of 7 to 600 miles from explosions at the Nevada Test Site.

A critical examination of a great many acoustic recordings at distances greater than 1000 km from explosions in the yield range from 1 to 500 KT equivalent led to use of the visually observed signal periods in the vicinity of maximum amplitude (uncorrected for response) for standard recordings as the best indicator of yield. Figure 3.2

* Formerly of the Navy Electronics Laboratory; now with the Marine Geophysical Laboratory, Scripps Institution of Oceanography.

shows a log-log plot of yield against observed period. Periods were selected from downwind or cross wind stations in the northern hemisphere for summer and winter propagation conditions and from all stations during spring and fall conditions. For each shot, the periods from these selected stations were averaged and these averages were plotted as shown in the figure. Stations exhibiting very low signal-to-noise ratio or very confused frequency patterns were eliminated.

Similar periods were selected from standard recordings of the direct wave from the megaton shots of IVY and CASTLE. These data are also plotted in Fig. 3.2. Care was taken to eliminate the dispersive train from consideration as far as possible in selecting the appropriate signal period since it was believed that this train depended mainly on the structure of the atmosphere rather than the size of the source.

A best power-law curve was computed by the method of least-squares for data up to and including yields of 500 KT. This curve indicated the yield to be equal to a constant times the period raised to roughly the third power. The standard error of estimate was also computed and the 3-standard error lines were plotted on Fig. 3.2.

It was noted that data for yields above about 100 KT fell along a curve of different slope from that at lower yields. The best curve in this region indicated the yield to be equal to a constant times the period raised to roughly the fourth power.

Very large errors are inherent in this method of determining yield from acoustic measurements. For yields up to about 100 KT, 3 standard errors of estimate cover yields as small as one-fifth and as large as five times the correct value. Errors at yields above roughly 100 KT seem slightly smaller although a correction for the small sample has been applied. Three standard errors cover yields as small as one-third and as large as three times the correct value at these higher yields.

Studies of the accuracy of yield determinations from the VLF recordings are being made by AFCRC and will be reported in a separate report at a later date. Effort is being centered on measurement of amplitude for these recordings.

Many other general indicators of yield were apparent. For instance, the existence of a dispersive train was apparent on graphic records only for shots with yields of 1.7 MT and greater. Also, the greater detection ranges, larger numbers of stations recording, and the generally higher amplitudes all were indicative of larger shots.

CHAPTER 4

CONCLUSIONS AND RECOMMENDATIONS

4.1 CONCLUSIONS

4.1.1 Detection Range

Results from CASTLE confirm results obtained from IVY and from previous nuclear detonations regarding the range of detection. With standard equipment it was possible to detect megaton shots at very great distances (usually at least 25,000 km). Ranges for VLF equipment, while still considerable, were generally appreciably less than for standard equipment. Range for the low kiloton shot was greatly reduced but was greater than the 4000 km normally considered desirable for effective detection net operations.

4.1.2 Signal Characteristics

The characteristics of acoustic signals from the CASTLE detonations were similar to that observed for previous tests. All megaton shots showed dispersive waves while the kiloton shot did not; horizontal phase velocities showed considerable spread but covered the same range of values previously observed; amplitudes ranged from a tenth of a dyne/cm^2 to several hundred dynes/cm^2 depending on the equipment, size of shot, distance from source, and noise level; signals persisted for a very long time; and signal periods spread over more than 8 octaves, from 3 to 450 sec.

CASTLE data definitely proved that dispersive waves may be generated by shots having a yield as low as 1.7 MT. These dispersive waves seemed to be modified by the atmospheric structure along the path from the source to the station.

4.1.3 Travel Speeds

Greatest travel speeds were normally observed for the long-period dispersive waves, but in a few instances much shorter-period waves were propagated over a few thousand kilometers at these same

speeds. The maximum speed of travel, 335 meters/second, was roughly equal to the speed of sound at ground level.

Travel speeds for direct waves on standard equipment showed somewhat greater variability than did the speeds for IVY.

4.1.4 Azimuth Errors

Azimuth errors observed for CASTLE were consistent with those observed on previous tests. Errors in the azimuths computed for the dispersive train were roughly the same as the errors for later portions of the wave train.

4.1.5 Yield

For megaton shots, the yield is given very approximately as a constant times the fourth power of the period at maximum amplitude for standard equipment. The method of measuring the period is somewhat subjective and the relationship between yield and period is very inaccurate. In addition, it should be noted that the method requires measurements at a number of stations for each shot in order to achieve even the semi-quantitative results reported here.

4.1.6 Directional Effects

The shift noted in travel speeds (speeds toward the east greater than that toward the west in March shifting to the opposite in May) were consistent with previous observations. This indicates that April was the change-over month for stratosphere winds.

4.1.7 Equipment

Standard equipment was superior to VLF equipment for detection purposes and provided a convenient, though inaccurate, means of estimating yield. In addition, most standard recordings showed some evidence of the dispersive train though with greatly reduced amplitude at the longer periods. It remains to be seen whether VLF recordings of the longer periods will give an accurate estimate of yield.

4.2 RECOMMENDATIONS

Recommendations for future participation in tests of megaton weapons must await the results of studies by AFCRC.

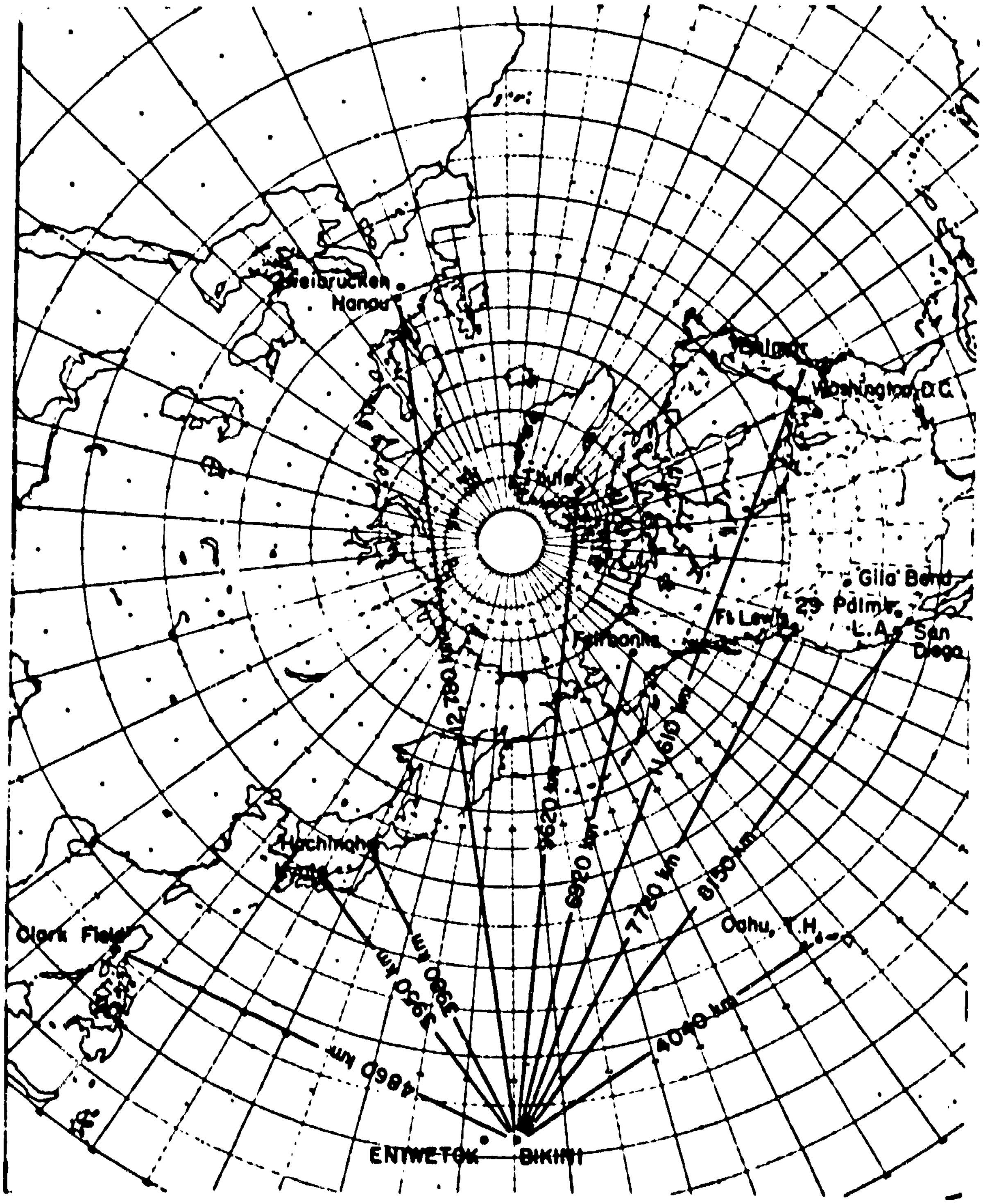

Fig. 2.1 Acoustic Stations, Operation CASTLE

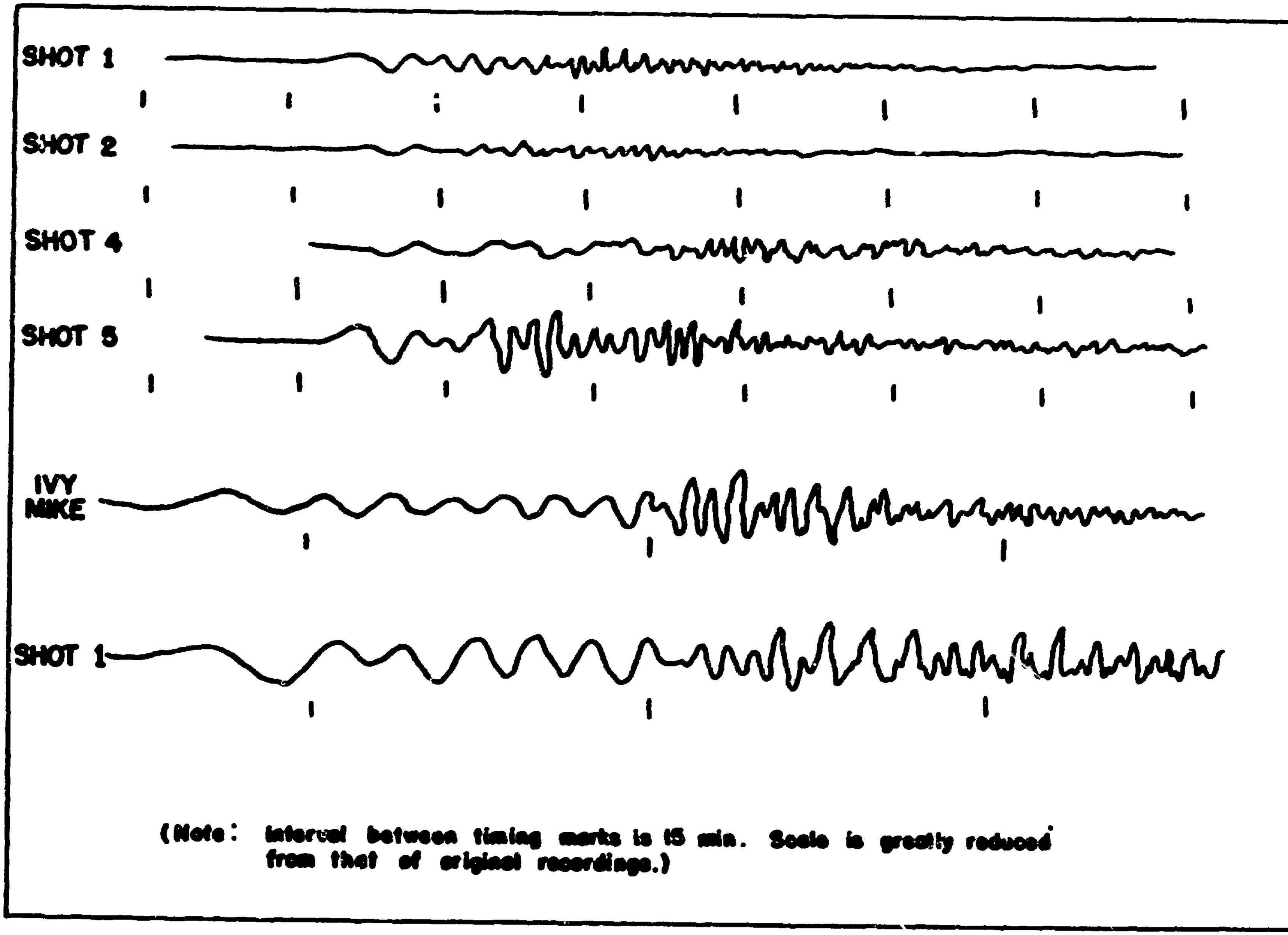

Fig. 3.1 Characteristic Very Low-Frequency Recordings, NEL, California-Arizona Region, CASTLE and IVY

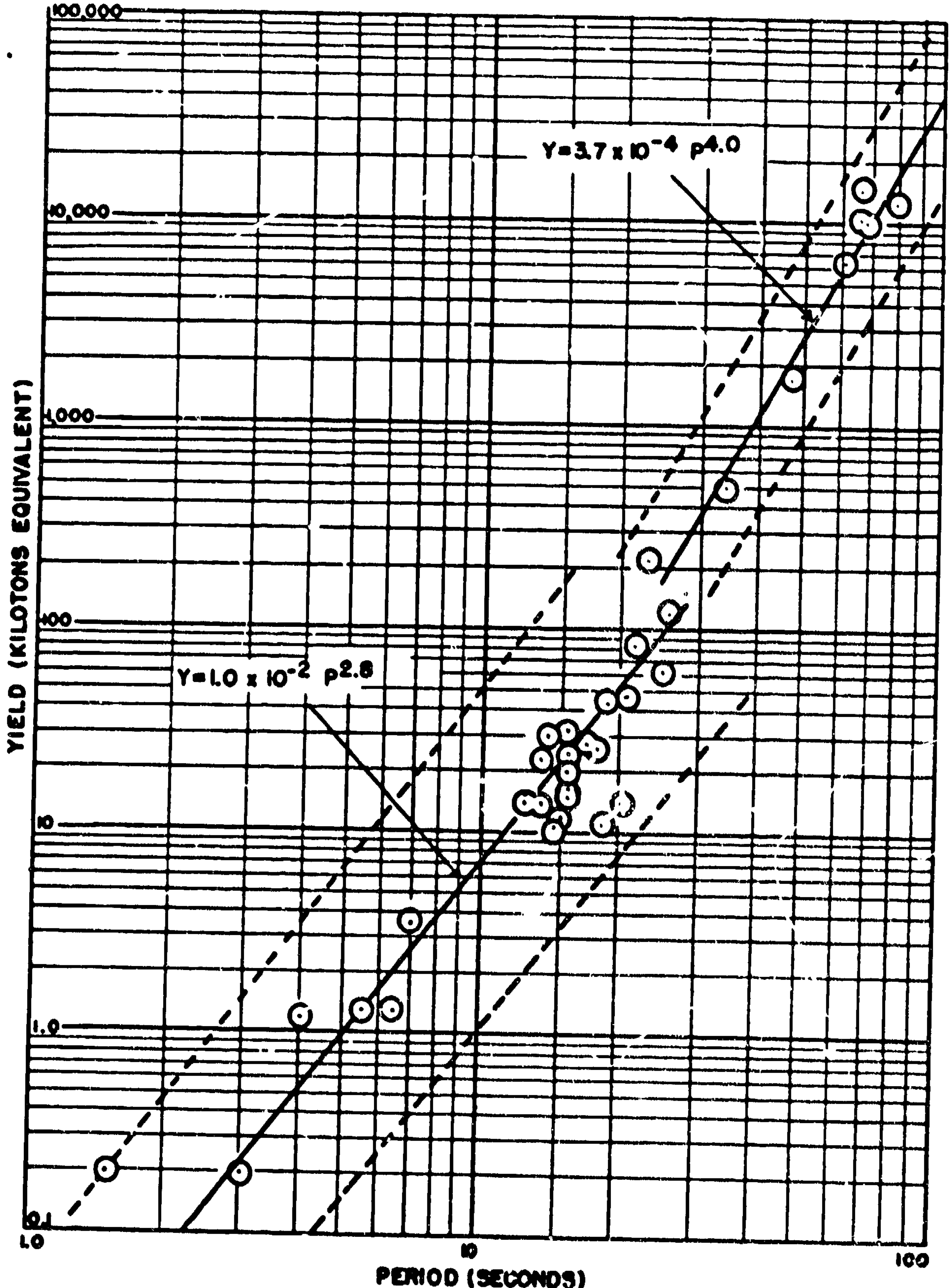

Fig. 3.2 Relation of Signal Period at Maximum Amplitude to Yield of Nuclear Shots, Standard Equipment

TABLE 2.1 CASTLE Remote Acoustic Station List

Agency	Station	Location		Azimuth from Station to		Distance from Station to	
		Latitude	Longitude	Bikini	Eniwetok	Bikini	Eniwetok
SCEL*	Kyoto, Japan	34°55'N	135°45'E	128°	124°	3950	3720
SCEL	Hachinohe, Japan	40°35'N	141°25'E	137°	142°	3980	3800
SCEL	Oahu, T. H.	21°31'N	158°05'W	260°	262°	4040	4380
SCEL	Clark Field, P. I.	15°11'N	120°34'E	089°	090°	4860	4520
SCEL	Fairbanks, Alaska	64°50'N	147°40'W	234°	237°	6920	7030
SCEL	Ft. Lewis, Wash.	47°05'N	122°35'W	265°	267°	7720	7950
NEL*	Los Angeles, Calif.	34°07'N	118°17'W	272.3°	-	8040	8320
NEL	San Diego, Calif.	32°42'N	117°15'W	273.3°	-	8150	8430
NEL	29 Palms, Calif.	34°14'N	116°02'W	273.5°	-	8250	8530
NEL	Gila Bend, Arizona	32°52'N	112°47'W	275.6°	-	8550	8830
SCEL	Thule, Greenland	76°32'N	068°40'W	307.5°	311°	9620	9670
NBS*	Washington, D. C.	38°57'N	077°04'W	297°	299°	11,460	11,700
SCEL	Belmar, N. J.	40°12'N	074°05'W	299°	302°	11,610	18,840
SCEL	Hanau, Germany	50°07'N	008°56'E	026°	029°	12,780	12,670
SCEL	Zweibrucken, Germany	49°14'N	007°28'E	024°	028°	12,910	12,800
AFCRC*	Darwin, Australia	12°30'S	130°50'E	-	-	4640	4370
AFCRC	Miami, Florida	25°50'N	080°10'W	-	-	11,780	-
AFCRC	Puerto Rico	18°20'N	066°15'W	-	-	13,380	13,670
AFCRC	Durban, S. Africa	29°30'S	030°20'E	-	-	14,890	-
AFCRC	Recife, Brazil	08°00'S	035°00'W	-	-	17,770	18,100

* SCEL - Signal Corps Engineering Laboratories
NEL - Navy Electronics Laboratory
AFCRC - Air Force Cambridge Research Center
NBS - National Bureau of Standards

TABLE 2.2 CASTLE Shot Data

	Shot 1	Shot 2	Shot 3	Shot 4	Shot 5	Shot 6
Date* (GMT)	28 Feb	26 Mar	06 Apr	25 Apr	04 May	13 May
Unclassified Code Name	BRAVO	ROMEO	KOON	UNION	YANKEE	NECTAR
Time (GMT) Hrs Min Sec	18:45:00	18:30:00	18:20:00	18:10:01	18:10:00	18:20:00
Location Latitude	11°41'26.9"N	18-ft N of BRAVO	11°29'48.0"N	11°39'58.5"N	11°39'58.5"N	11°40'13.9"N
Longitude	165°16'24.8"E	204-ft W of BRAVO	165°22'03.4"E	165°23'13.7"E	165°23'13.7"E	162°11'46.8"E
Type (All essentially surface shots)	Land	Barge	Land	Barge	Barge	Barge
Yield** (Megatons Equivalent)	15.0 ± 0.5	11 ± 0.5	0.110 ± 0.020	7.0 ± 0.3	13.5 ± 1.0	1.7 ± 0.3

* All shot dates were in 1954.

** Contained in letter from CG, AFSWP Field Command, FCWET 12-4-6556, dated 10 December 1954.

TABLE 3.1 - Acoustic Data for CASTLE Shot 1, Standard Equipment

(Source Time: 28 February 1954, 1845:00 GMT)

Station	Time of Arrival (GMT) Start (Date, hr, min)	Time of Arrival (GMT) Max Ampl (Hr,min)	Average Computed Azimuth (degrees)	Horizontal Phase Velocities (meters/sec)	Max Signal Amplitude O-peak (dynes/cm²)	Signal Duration (min)	Signal Periods (sec)	Average Noise O-peak (dynes/cm²)
				First Wave	(Direct)			
Kyoto	282220	2235	128	315 - 402	> 34	30	250-40	2.8
Hachinohe	282221	2242	137	294 - 347	> 12	96	205-20	1.2
Oahu	282206	2233	263	305 - 430	> 39	108	100-03	2.6
Fairbanks	010048	0116	231	325 - 375	47	31	140-07	0.8
Ft. Lewis	010127	0149 ?	269	332 - 370	> 33	48	280-05	1.5
Thule	010330	0338	300	304 - 325	49	31	47-05	10.5
Wash., D.C.	010512	0512	302	340	?	17	107	?
Belmar	010525	0527	295	343 - 402	9.0	13	45-20	1.[illegible]
Hanau	010653	0724	352	288 - 352	5.0	67	115-10	0.6

Not in Operation: Clark Field and Zweibrucken

TABLE 3.1 - Acoustic Data for CASTLE Shot 1, Standard Equipment (Contd)

(Source Time: 28 February 1954, 1845:00 GMT)

Station	Time of Arrival (GMT) Start (Date, hr, min)	Time of Arrival (GMT) Max Ampl (Hr,min)	Average Computed Azimuth (degrees)	Horizontal Phase Velocities (meters/sec)	Max Signal Amplitude O-peak (dynes/cm^2)	Signal Duration (min)	Signal Periods (sec)	Average Noise O-peak (dynes/cm^2)
				Second Wave	(Antirodes)			
Hanau	011951	2042	203	320 - 389	5.0	208	105-20	0.9
Thule	020007	0011	109	306 - 352	2.3	34	60-13	1.0
Oahu	020304	0427	121	302 - 393	3.3	101	205-50	1.2
Hachinohe	020325	0331	303	325	[illegible]	17	210-170	4.2
				Third Wave (Second	Direct)			
Kyoto	021139	1147	234	320 - 366	4.5	16	60-50	3.8
Ft. Lewis	021429	1559	279	270 - 489	6.5	166	190-25	1.4
Thule	021716	1718	289	292 - 344	1.5	73	50-17	0.7
Wash., D.C.	022019	2024	298	369	2.2	81	40	2.0

Not in Operation: Clark Field and Zweibrucken

TABLE 3.2 - Acoustic Data for CASTLE Shot 1, Very Low-Frequency Equipment

(Source Time: 28 February 1954, 1845:00 GMT)

Station	Time of Arrival (GMT) Start (Date, hr, min)	Time of Arrival (GMT) Max Ampl (Hr, min)	Average Computed Azimuth (degrees)	Horizontal Phase Velocities (meters/sec)	Max Signal Amplitude 0-peak (dynes/cm^2)	Signal Duration (min)	Signal Periods (sec)	Average Noise 0-peak (dynes/cm^2)
				First Wave	(Direct)			
Los Angeles	010146	0215			190	50	390, 150, 125	10
San Diego	010151	0154	263	315 - 325	100	95	350, 160, 115	10
29 Palms	010157	0222			200	70	350, 135, 120	5
Gila Bend	010213	0240			100	130	360, 150, 115, 70	5
Wash., D.C.	010445	0529	297	323	145	44	109	~25
Belmar	010449	0511	294	395 - 800	48	41	420-35	1.7

Not in Operation: Kyoto, Oahu, Fairbanks, Ft. Lewis, and Hanau

TABLE 3.2 - Acoustic Data for CASTLE Shot 1, Very Low-Frequency Equipment (Contd)

(Source Time: 28 February 1954, 1845:00 GMT)

Station	Time of Arrival (GMT) Start (Date, hr, min)	Time of Arrival (GMT) Max Ampl (Hr, min)	Average Computed Azimuth (degrees)	Horizontal Phase Velocities (meters/sec)	Max Signal Amplitude O-peak (dynes/cm²)	Signal Duration (min)	Signal Periods (sec)	Average Noise O-peak (dynes/cm²)
			Third Wave (Second Direct)					
Los Angeles	021256	1306			47	~240	420, 210, 175, 120	22
San Diego	021301	1308	271	345 - 355	~ 41	~ 240	400, 200, 170, 120	18
29 Palms	021307	1307			~127	~113	450, 180	34

Not in Operation: Kyoto, Ft. Lewis, Gila Bend, and Hanau

TABLE 3.3 - Acoustic Data for CASTLE Shot 2, Standard Equipment

(Source Time: 26 March 1954, 1830:00 GMT)

Station	Time of Arrival (GMT) Start (Date, hr, min)	Max Ampl (Hr, min)	Average Computed Azimuth (degrees)	Horizontal Phase Velocities (meters/sec)	Max Signal Amplitude O-peak (dynes/cm^2)	Signal Duration (min)	Signal Periods (sec)	Average Noise O-peak (dynes/cm^2)
				First Wave	(Direct)			
Kyoto	262204	2218	126	288 - 366	>38	113	275-15	1.3
Hachinohe	262209	2227 ?	137	302 - 338	>42	41	165-30	8.5
Oahu	262202	2213 ?	264	311 - 338	>57	38	200-15	2.5
Clark Field	262254	2316	094	309 - 358	>11	94	110-20	0.2
Fairbanks	270036	0059	237	327 - 352	6.0	102	145-10	0.4
Ft. Lewis	270132	0138	265	329 - 389	13	39	105-25	11.5
Thule	270309	0324	313	288 - 335	14	81	120-08	1.5
Wash., D.C.	270456	0503	284	354	14	304	21	5.6
Belmar	270502	0520	293	323 - 389	5.0	34	95-15	0.9
Hanau	270611	0622	020	299 - 372	> 6.0	102	105-15	0.7
Zweibrucken	270614	0628	004	305 - 324	18	45	110-22	1.3

TABLE 3.3 - Acoustic Data for CASTLE Shot 2, Standard Equipment (Contd)

(Source Time: 26 March 1954, 1830:00 GMT)

Station	Time of Arrival (GMT) Start (Date, hr, min)	Time of Arrival (GMT) Max Ampl (hr, min)	Average Computed Azimuth (degrees)	Horizontal Phase Velocities (meters/sec)	Max Signal Amplitude 0-peak (dynes/cm^2)	Signal Duration (min)	Signal Periods (sec)	Average Noise 0-peak (dynes/cm^2)
				Second Wave	(Antipodes)			
Zweibrucken	271830	2022	205	280 - 392	10	266	220-20	0.9
Hanau	271916	2030	202	291 - 316	6.5	91	125-15	0.4
Wash., D.C.	272130	2310	132	314	2.5	530	75, 60	0.8
Thule	272254	2349	114	301 - 337	5.0	87	43-08	1.2
Fairbanks	280134	0225	054	288 - 346	3.0	119	95-21	0.4
Oahu	280434	0557	097	275 - 373	3.5	133	95-35	0.8
Hachinohe	280451	0453	308	327 - 377	4.0	21	65-18	1.2
			Third Wave	(Second Direct)				
Hachinohe	281345	1411	117	271 - 352	4.2	63	76-55	2.4
Clark Field	281434	1740	090	311 - 384	1.2	356	60-20	0.8
Fairbanks	281357	1358	160	295 - 324	0.7	10	40-30	0.4

TABLE 3.4 - Acoustic Data for CASTLE Shot 2, Very Low-Frequency Equipment

(Source Time: 26 March 1954, 1830:00 GMT)

Station	Time of Arrival (GMT)		Average Computed Azimuth (degrees)	Horizontal Phase Velocities (meters/sec)	Max Signal Amplitude O-peak (dynes/cm^2)	Signal Duration (min)	Signal Periods (sec)	Average Noise O-peak (dynes/cm^2)
	Start (Date, hr, min)	Max Ampl (Hr, min)						
				First Wave	(Direct)			
Oahu	262203	2214	268	306 - 338	87	23	180-15	23
Fairbanks	270035	0054	238	326 - 499	> 40	127	275-30	1.0
Ft. Lewis	270106	0126	242	375	12	39	300-50	0.6
Los Angeles	270125	0145			100	50	440, 120, 80	10
San Diego	270130	0146	269	322 - 327	85	140	430, 140, 90	15
29 Palms	270135	0150			100	~110	400, 130, 85	10
Gila Bend	270152	0221			~100	240	400, 140, 95	25
Wash., D.C.	270416	0457	286	340	25	72	448, 112	20
Belmar	270458	0509	300	352 - 361	22	36	125-24	12

Not in Operation: Kyoto, Hanau

TABLE 3.4 – Acoustic Data for CASTLE Shot 2, Very Low-Frequency Equipment (Contd)

(Source Time: 26 March 1954, 1830:00 GMT)

Station	Time of Arrival (GMT)		Average Computed Azimuth (degrees)	Horizontal Phase Velocities (meters/sec)	Max Signal Amplitude 0-peak (dynes/cm^2)	Signal Duration (min)	Signal Periods (sec)	Average Noise 0-peak (dynes/cm^2)
	Start (Date, hr, min)	Max Ampl (Hr, min)						
				Second Wave	(Antipodes)			
Fairbanks	270030	0055	054	288 - 366	11	173	265-40	0.5
Oahu	280512	0611	098	285 - 312	7	33	100-50	1.0

Not in Operation: Kyoto, Hanau

TABLE 3.5 - Acoustic Data for CASTLE Shot 3

(Source Time: 06 April 1954, 1820:00 GMT)

Station	Time of Arrival (GMT)		Average Computed Azimuth (degrees)	Horizontal Phase Velocities (meters/sec)	Max Signal Amplitude 0-peak (dynes/cm^2)	Signal Duration (min)	Signal Periods (sec)	Average Noise 0-peak (dynes/cm^2)
	Start (Date, hr, min)	Max Ampl (Hr, min)						
		First	Wave	(Direct)	Standard	Equipment		
Oahu	062156	2200	262	320 - 347	6.5	40	45-15	1.2
Clark Field	062300	2305	095	312 - 375	2.1	24	40-15	0.3
Fairbanks	070047	0059	234	325 - 366	1.4	36	50-20	0.7
Wash., D.C.	070652	0935	297	350	0.7	369	30, 40	0.6
	First	Wave	(Direct)	Very Low -	Frequency	Equipment		
Oahu	062157	2200	265	341 - 364	7.0	33	50-15	1.0

TABLE 3.6 – Acoustic Data for CASTLE Shot 4, Standard Equipment

(Source Time: 25 April 1954, 1810:01 GMT)

Station	Time of Arrival (GMT)		Average Computed Azimuth (degrees)	Horizontal Phase Velocities (meters/sec)	Max Signal Amplitude 0-peak (dynes/cm^2)	Signal Duration (min)	Signal Periods (sec)	Average Noise 0-peak (dynes/cm^2)
	Start (Date, hr, min)	Max Ampl (Hr, min)		First Wave	(Direct)			
Kyoto	252137	2150	124	296 - 429	> 33	51	290-20	1.6
Hachinohe	252145	2155	141	322 - 326	37	33	195-20	1.1
Oahu	252152	2202	260	349 - 350	15	17	85-08	3.3
Clark Field	252224	2251	089	329 - 416	8.5	78	125-16	0.4
Fairbanks	260024	0033	233	295 - 343	5.5	66	120-12	0.4
Ft. Lewis	260109	0109	266	336 - 358	8.0	48	145-11	3.1
Thule	260257	0314	314	284 - 316	4.2	81	105-15	0.7
Wash., D.C.	260432	0439	302	340	?	363	107	?
Belmar	260446	0551	300	316 - 348	2.8	80	95-35	1.0
Hanau	260557	0614	026	326 - 369	> 14	50	125-15	0.5
Zweibrucken	260554	0623	020	309 - 346	26	51	215-30	1.0

TABLE 3.6 - Acoustic Data for CASTLE Shot 4, Standard Equipment (Contd)

(Source Time: 25 April 1954, 1810:01 GMT)

Station	Time of Arrival (GMT)		Average Computed Azimuth (degrees)	Horizontal Phase Velocities (meters/sec)	Max Signal Amplitude O-peak (dynes/cm^2)	Signal Duration (min)	Signal Periods (sec)	Average Noise O-peak (dynes/cm^2)
	Start (Date, hr, min)	Max Ampl (Hr, min)						
				Second Wave	(Antipodes)			
Belmar	262256	2347	125	268 - 399	3.7	161	95-15	1.9
Wash., D.C.	270002	0008	127	316	3.1	12	33	1.7
Thule	262333	0053	102	316 - 360	1.5	109	90-20	0.4
Ft. Lewis	270246	0340	085	274 - 351	5.0	329	140-30	0.5
			Third	Wave (Second	Direct)			
Clark Field	271327	1608	088	283 - 389	1.3	368	85-25	0.7
Fairbanks	271400	1401	192	289 - 323	1.0	31	60-30	0.4
			Fourth	Wave (Second	Antipodes)			
Clark Field	262135	2203	292	346 - 389	0.5	50	70-40	0.2

TABLE 3.7 - Acoustic Data for CASTLE Shot 4, Very Low-Frequency Equipment

(Source Time: 25 April 1954, 1810:01 GMT)

Station	Time of Arrival (GMT)		Average Computed Azimuth (degrees)	Horizontal Phase Velocities (meters/sec)	Max Signal Amplitude 0-peak (dynes/cm^2)	Signal Duration (min)	Signal Periods (sec)	Average Noise 0-peak (dynes/cm^2)
	Start (Date, hr, min)	Max Ampl (Hr,min)						
				First Wave	(Direct)			
Kyoto	252136	2155	126	298 - 344	24	42	455-34	0.2
Oahu	252141	2202	266	315 - 327	46	33	235-26	4.8
Fairbanks	260018	0034	239	325 - 365	30	90	250-30	0.8
Ft. Lewis	260103	0114	261	347 - 416	19	84	210-18	4.4
Los Angeles	260105	0125			50	120	240, 160, 75	20
San Diego	260111	0150	267	317 - 325	50	125	240, 160, 75	20
29 Palms	260115	0150			25	105	330, [illegible], 150, 75	~10
Gila Bend	260132	0208			~ 25	100	340, 160, 70	~20
Wash., D.C.	260433	0542	305	333	?	69	107	?
Belmar	260440	0446	301	301 - 303	6	73	120-50	1.1
Hanau	260544	0604	027	274 - 334	?	49	250-50	?

SECRET – RESTRICTED DATA

TABLE 3.7 - Acoustic Data for CASTLE Shot 4, Very Low-Frequency Equipment (Contd)

(Source Time: 25 April 1954, 1810:01 GMT)

Station	Time of Arrival (GMT)		Average Computed Azimuth (degrees)	Horizontal Phase Velocities (meters/sec)	Max Signal Amplitude O-peak (dynes/cm^2)	Signal Duration (min)	Signal Periods (sec)	Average Noise O-peak (dynes/cm^2)
	Start (Date, hr, min)	Max Ampl (Hr, min)						
				<u>Second Wave</u>	<u>(Antipodes)</u>			
Belmar	262254	2347	125	268 - 327	~ 9	134	125-30	2.3
Ft. Lewis	270130	0510	092	263 - 321	9	339	285-30	2.0

TABLE 3.8 - Acoustic Data for CASTLE Shot 5, Standard Equipment

(Source Time: 04 May 1954, 1810:00 GMT)

Station	Time of Arrival (GMT)		Average Computed Azimuth (degrees)	Horizontal Phase Velocities (meters/sec)	Max Signal Amplitude O-peak (dynes/cm²)	Signal Duration (min)	Signal Periods (sec)	Average Noise O-peak (dynes/cm²)
	Start (Date, hr, min)	Max Ampl (Hr, min)						
				First Wave	(Direct)			
Kyoto	042143	2200	118	310 - 352	> 41	32	210-35	1.0
Hachinohe	042143	2159	143	264 - 389	> 36	26	205-30	3.8
Oahu	042141	2150	258	320 - 331	> 46	28	130-20	10
Clark Field	042228	2249	096	329 - 395	12	108	235-12	0.3
Fairbanks	050032	0042	240	315 - 326	14	21	120-12	1.6
Ft. Lewis	050109	0139	266	341 - 381	27	59	135-15	4.4
Thule	050307	0311	319	279	28	8	35-20	14
Wash., D.C.	050438	0438	296	360	54	192	120	
Belmar	050437	0519	297	300 - 348	8.0	107	185-25	0.6
Hanau	050542	0600	030	310 - 398	7.5	219	120-20	0.3
Zweibrucken	050548	0605	021	317 - 343	5.0	42	125-20	0.3

TABLE 3.8 - Acoustic Data for CASTLE Shot 5, Standard Equipment (Contd)

(Source Time: 04 May 1954, 1810:00 GMT)

Station	Time of Arrival (GMT) Start (Date, hr, min)	Time of Arrival (GMT) Max Ampl (Hr, min)	Average Computed Azimuth (degrees)	Horizontal Phase Velocities (meters/sec)	Max Signal Amplitude 0-peak (dynes/cm^2)	Signal Duration (min)	Signal Periods (sec)	Ave'age Noise 0-peak (dynes/cm^2)
				Second Wave	(Antipodes)			
Zweibrucken	051850	1921	218	296 - 377	4.3	49	110-22	3.5
Hanau	051857	2007	200	281 - 338	2.7	73	63-25	0.6
Belmar	052316	0031	115	312 - 377	> 5.0	168	150-35	0.9
Wash., D.C.	052255	0034	116	318	3.5	490	55, 35	0.4
Thule	052340	0012	099	300 - 359	3.2	110	70-20	1.2
Ft. Lewis	060311	0334	083	324 - 373	8.0	113	85-32	1.7
Fairbanks	060217	0237	025	302 - 338	2.1	47	75-40	0.5
Clark Field	060620	0621	281	302	3.4	3	45	2.2
			Third	Wave (Second	Direct)			
Clark Field	061410	1644	103	305 - 406	1.1	335	90-15	0.3
Hanau	062050	2055	353	289 - 351	2.0	33	35-16	0.6
			Fourth	Wave (Second	Antipodes)			
Clark Field	071932	1935	324	369 - 379	0.5	8	40-25	0.2

TABLE 3.9 - Acoustic Data for CASTLE Shot 5, Very Low-Frequency Equipment

(Source Time: 04 May 1954, 1810:00 GMT)

Station	Time of Arrival (GMT) Start (Date,hr,min)	Time of Arrival (GMT) Max Ampl (Hr,min)	Average Computed Azimuth (degrees)	Horizontal Phase Velocities (meters/sec)	Max Signal Amplitude 0-peak (dynes/cm^2)	Signal Duration (min)	Signal Periods (sec)	Average Noise 0-peak (dynes/cm^2)
				First Wave	(Direct)			
Kyoto	042145	2200	124	294 - 358	27	60	215-30	0.2
Oahu	042145	2155	252	287 - 310	> 73	32	140-60	24
Fairbanks	050021	0041	232	315 - 355	> 80	61	230-30	7.0
Ft. Lewis	050053	0139	255	372 - 375	> 47	111	320-30	7.0
Los Angeles	050114	0132			135	110	345, 130, 85	15
San Diego	050119	0138	271	315 - 325	100	140	360, 130, 90	10
29 Palms	050125	0143			>100	115	330, 135, 100	15
Gila Bend	050141	0200			~100	140	360, 130, 90	15
Wash., D.C.	050422	0442	292	327	37	192	260, 132	10
Belmar	050430	0510	297	325 - 360	12	84	240-36	0.6
Hanau	050531	0548	026	291	?	33	240-40	?

TABLE 3.9 - Acoustic Data for CASTLE Shot 5, Very Low Frequency Equipment (Contd)

(Source Time: 04 May 1954, 1810:00 GMT)

Station	Time of Arriv (GMT)		Average Computed Azimuth (degrees)	Horizontal Phase Velocities (meters/sec)	Max Signal Amplitude 0-peak (dynes/cm^2)	Signal Duration (min)	Signal Periods (sec)	Average Noise 0-peak (dynes/cm^2)
	Start (Date, hr, min)	Max Ampl (Hr, min)						
				Second Wave	(Antipodes)			
Belmar	052310	0031	110	291 - 332	8.5	170	155-45	2.9
Wash., D. C.	052225	2225	120	329	19	305	220	10
Ft. Lewis	060313	0316	085	315 - 362	18	220	205-40	7.5
Fairbanks	060214	0237	027	288 - 426	13	91	120-40	0.2

TABLE 3.10 - Acoustic Data for CASTLE Shot 6, Standard Equipment

(Source Time: 13 May 1954, 1820:00 GMT)

Station	Time of Arrival (GMT)		Average Computed Azimuth (degrees)	Horizontal Phase Velocities (meters/sec)	Max Signal Amplitude O-peak (dynes/cm^2)	Signal Duration (min)	Signal Periods (sec)	Average Noise O-peak (dynes/cm^2)
	Start (Date, hr, min)	Max Ampl (Hr, min)						
				First Wave	(Direct)			
Kyoto	132138	2147	129	342 - 362	> 35	67	220-14	2.2
Hachinohe	132144	2150	143	315 - 342	> 21	31	170-10	2.6
Oahu	132229	2241	264	336 - 355	11	14	100-22	4.0
Clark Field	132215	2230	090	343 - 421	> 14	74	75-05	0.3
Fairbanks	140053	0056	237	320 - 334	3.0	9	80-15	1.6
Ft. Lewis	140154	0213	268	323 - 424	6.0	46	80-25	3.4
Thule	140312	0328	314	292 - 347	3.0	128	115-12	0.8
Wash., D.C.	140518	0545	303	318	3.6	70	50	3.6
Belmar	140527	0533	300	321 - 347	2.2	44	100-30	1.0
Hanau	140550	0557	031	313 - 375	2.7	76	75-25	0.3
Zweibrucken	140559	0602	023	278 - 337	5.5	13	85-30	1.5

TABLE 3.10 - Acoustic Data for CASTLE Shot 6, Standard Equipment (Contd)

(Source Time: 13 May 1954, 1820:00 GMT)

Station	Time of Arrival (GMT) Start (Date, hr, min)	Time of Arrival (GMT) Max Ampl (Hr, min)	Average Computed Azimuth (degrees)	Horizontal Phase Velocities (meters/sec)	Max Signal Amplitude O-peak (dynes/cm²)	Signal Duration (min)	Signal Periods (sec)	Average Noise O-peak (dynes/cm²)
				Second Wave	(Antipodes)			
Thule	150043	0058	099	294 - 336	1.0	96	50-20	1.0
Ft. Lewis	150243	0333	062	206 - 358	2.2	354	140-35	1.3

TABLE 3.11 - Acoustic Data for CASTLE Shot 6, Very Low-Frequency Equipment

(Source Time: 13 May 1954, 1820:00 GMT)

Station	Time of Arrival (GMT) Start (Date, hr, min)	Time of Arrival (GMT) Max Ampl (Hr, min)	Average Computed Azimuth (degrees)	Horizontal Phase Velocities (meters/sec)	Max Signal Amplitude 0-peak (dynes/cm^2)	Signal Duration (min)	Signal Periods (sec)	Average Noise 0-peak (dynes/cm^2)
				First Wave	(Direct)			
Kyoto	132138	2144	127	358 - 391	13	70	215-10	0.3
Oahu	132227 ?	2259 ?	265 ?	317 - 358 ?	24 ?	33 ?	164-60 ?	12
Fairbanks	140050	0056	240	314 ?	11	9	175-60	4.8
Ft. Lewis	140153	0200	251	347	~10	45	80-30	3.9
Belmar	140530	0533	292	326 - 374	3.2	45	80-40	1.7
Hanau	140550	0555	031	439 - 478	?	25	65-30	?

TABLE 3.12 Travel Speeds for First Acoustic Arrivals, Standard Equipment, Operation CASTLE

Station	Travel Speed (Meters/sec)					
	Shot 1	Shot 2	Shot 3	Shot 4	Shot 5	Shot 6
			First Wave (Direct)			
Kyoto	306	307	-	318	309	313
Hachinobe	307	302	-	308	311	311
Oahu	335	318	312	303	318	292
Clark Field	NIO	306	289	319	314	320
Fairbanks	317	315	298	308	301	298
Ft. Lewis	320	305	-	307	307	292
Thule	305	309	-	304	298	303
Wash., D.C.	305	302	254	307	304	293
Belmar	302	306	-	304	315	296
Hanau	292	304	-	301	308	306
Zweibrucken	NIO	305	-	306	308	305
			Second Wave (Antipodes)			
Zweibrucken	NIO	314	-	-	305	-
Hanau	302	306	-	-	306	-
Belmar	-	-	-	274	271	-
Wash., D.C.	-	286	-	265	268	-
Thule	288	298	-	288	286	278
Ft. Lewis	-	-	-	276	272	275
Fairbanks	-	296	-	-	286	-
Clark Field	-	-	-	-	270	-
Oahu	309	293	-	-	-	-
Hachinobe	307	292	-	-	-	-
Kyoto	-	-	-	-	-	-

TABLE 3.12 Travel Speeds for First Acoustic Arrivals, Standard Equipment, Operation CASTLE (Contd)

Station	Travel Speed (Meters/sec)					
	Shot 1	Shot 2	Shot 3	Shot 4	Shot 5	Shot 6
	Third Wave (Second Direct)					
Kyoto	299	-	-	-	-	-
Hachinohe	-	283	-	-	-	-
Clark Field	-	283	-	288	283	-
Fairbanks	-	300	-	297	-	-
Ft. Lewis	303	-	-	-	-	-
Thule	296	-	-	-	-	-
Wash., D.C.	288	-	-	-	-	-
Hanau	-	-	-	-	289	-
	Fourth Wave (Second Antipodes)					
Clark Field	-	-	-	277	285	-

TABLE 3.13 Travel Speeds for First Acoustic Arrivals, Very Low-Frequency Equipment, Operation CASTLE

Station	Travel Speed (Meters/sec)					
	Shot 1	Shot 2	Shot 3	Shot 4	Shot 5	Shot 6
		First Wave (Direct)				
Kyoto	NIO	NIO	-	320	306	313
Oahu	NIO	316	310	318	313	294
Fairbanks	NIO	316	-	313	310	301
Ft. Lewis	NIO	325	-	313	319	292
Los Angeles*	318	323	-	322	316	-
San Diego*	318	323	-	322	316	-
29 Palms*	318	323	-	322	316	-
Gila Bend*	318	322	-	322	316	-
Wash., D.C.	318	326	-	307	312	293
Belmar	316	308	-	307	318	295
Hanau	NIO	NIO	-	307	313	306
Darwin*	318	325	-	316	318	314
Miami*	324	328	-	323	318	-
Puerto Rico*	325	326	-	322	317	307
Durban*	NIO	314	-	312	311	-
Recife*	320	320	-	319	316	310

* Speed computed for arrival of first positive peak.

TABLE 3.13 Travel Speeds for First Acoustic Arrivals, Very Low-Frequency Equipment, Operation CASTLE (Contd)

Station	Travel Speed (Meters/sec)					
	Shot 1	Shot 2	Shot 3	Shot 4	Shot 5	Shot 6
		Second Wave (Antipodes)				
Belmar	-	-	-	275	272	-
Wash., D.C.	-	-	-	-	281	-
Ft. Lewis	NIO	-	-	287	272	-
Fairbanks	-	307	-	-	287	-
Oahu	-	288	-	-	-	-
Recife*	321	321	-	319	317	-
Durban*	-	328	-	326	322	-
		Third Wave (Second Direct)				
Los Angeles*	316	-	-	-	-	-
San Diego*	316	-	-	-	-	-
29 Palms*	316	-	-	-	-	NIO
Gila Bend*	NIO	-	-	-	-	-

* Speed computed for arrival of first positive peak.

TABLE 3.14 Azimuth Errors*, Standard Equipment
Operation CASTLE

Station	Azimuth Errors (Degrees)					
	Shot 1	Shot 2	Shot 3	Shot 4	Shot 5	Shot 6
		First Wave (Direct)				
Kyoto	4.3 SW	2.3 SW	-	0.4 SW	5.6 NE	1.4 SW
Hachinohe	0.3 NE	0.3 NE	-	3.9 SW	5.9 SW	1.2 SW
Oahu	2.7 N	3.7 N	2.0 N	0.2 S	2.2 S	2.0 N
Clark Field	NIO	5.1 S	5.8 S	0.1 S	7.1 S	0.3 S
Fairbanks	3.1 SE	2.9 NW	0.1 NW	1.0 SE	6.0 NW	0.3 SE
Ft. Lewis	4.0 NW	0.0	-	1.1 NW	1.1 NW	0.7 NW
Thule	7.6 E	5.4 W	-	6.5 W	11.5 W	3.5 W
Wash., D.C.	5.0 NW	11.0 SE	0.1 NW	5.0 NW	1.0 SE	3.8 NW
Belmar	4.5 SE	6.5 SE	-	0.6 NW	2.4 SE	1.8 SE
Hanau	33.7 E	5.7 E	-	0.4 W	4.4 W	2.2 W
Zweibrucken	NIO	20.3 E	-	4.2 E	3.2 E	4.5 E

* Difference between true azimuth and measured azimuth. "E" means indicated source is east of the true source; "N" means indicated source is north of true source; etc.

TABLE 3.14 Azimuth Errors, Standard Equipment, Operation CASTLE (Contd)

Station	Azimuth Errors (Degrees)					
	Shot 1	Shot 2	Shot 3	Shot 4	Shot 5	Shot 6
		Second Wave (Antipodes)				
Zweibrucken	-	0.7 W	-	-	13.8 W	-
Hanau	2.7 E	3.7 E	-	-	5.6 E	-
Belmar	-	-	-	5.6 NW	4.4 SE	-
Wash., D.C.	-	14.9 SE	-	10.0 SE	1.0 NW	-
Thule	18.6 E	13.6 E	-	25.5 E	28.5 E	31.5 E
Ft. Lewis	-	-	-	0.1 SE	1.9 SE	25.3 SE
Fairbanks	-	0.1 NW	-	-	29.0 SE	-
Clark Field	-	-	-	-	12.1 S	-
Oahu	40.7 N	16.7 N	-	-	-	-
Hachinohe	14.3 NE	8.7 SW	-	-	-	-
Kyoto	-	-	-	-	-	-
		Third Wave (Second Direct)				
Kyoto	110.3 SW	-	-	-	-	-
Hachinohe	-	20.3 NE	-	-	-	-
Clark Field	-	1.1 S	-	0.9 N	14.1 S	-
Fairbanks	-	74.1 SE	-	42.0 SE	-	-
Ft. Lewis	14.0 NW	-	-	-	-	-
Thule	18.6 E	-	-	-	-	-
Wash., D.C.	0.9 SE	-	-	-	-	-
Hanau	-	-	-	-	32.6 E	-
		Fourth Wave (Second Antipodes)				
Clark Field	-	-	-	23.1 S	55.1 S	-

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TRC 10 September 1997

MEMORANDUM FOR DEFENSE TECHNICAL INFORMATION CENTER
ATTENTION: OMI/Mr. William Bush

SUBJECT: Declassification of AD-361833L and Removal of AD-A995117 -[redacted]

S-FRD

The Defense Special Weapons Agency Security Office (OPSSI) has reviewed and declassified the following report:

~~AD-361833L~~ same WT-931
Operation CASTLE, Pacific Proving Grounds, March - May 1954, Project 7.2, Detection of Airborne Low-Frequency Sound From Nuclear Explosions, Report to the Test Director, dated May 1955.

Distribution statement **"A"** (approved for public release) now applies.

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